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Quantifying and Predicting Gully Erosion and its Contribution to Nutrient Pollution from Vermont's Roads

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An undergraduate thesis submitted in partial completion of College Honors

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Abstract

Water is a precious resource for human life and environmental health, however, human activity contributes a wide variety of contaminants to freshwater systems. Soil erosion adds nutrients, sediment, and pollutants to the water, and contributes to declining water quality downstream. Road networks are particularly important in this context, because roads interrupt the flow of water, often increasing the erosive power of adjacent materials, causing serious local erosion. Despite the importance of roads in the process of water quality impairment, little is known about the severity of this issue or the factors that drive it. This project investigates the magnitude of gully erosion as an issue on Vermont's roads. High-resolution three-dimensional scans of selected gullies are compared with municipal and state gully inventories to determine the general distribution and severity of these erosive features. Five towns were selected for a focused geospatial analysis of existing Road Erosion Inventory data to survey the magnitude of gully erosion on the local level. Contributing factors were statistically compared to determine what land features have the greatest effect on the probability of extreme erosion from concentrated outfalls. Soil tests were conducted to estimate the total mass of mobilized sediment-bound phosphorus associated with this form of erosion. The study's findings show that gully erosion from roads has the potential to mobilize up to hundreds of kilograms of sediment-bound phosphorus over the course of a single gully's development. Rough calculations using the results of this experiment indicate that gully erosion at concentrated outfalls could be producing nearly 11% of Lake Champlain's yearly phosphorus input. The study illuminates Vermont's need for more comprehensive surveys of existing road drainage features. The methods and findings of this research will inform further investigation of the phosphorus runoff reduction potential of repairs made to gullies at concentrated outfalls on Vermont's roads.

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Chapter 1: Introduction & Literature Review

Introduction

Human infrastructure, especially transportation networks, disturb natural water movement and can lead to significant pollution (USEPA, 2015, Vörösmarty, et. al. 2010). For example, when rivers and streams intersect road networks, harmful contaminants including phosphorus (P), heavy metals and sediment are mobilized and transferred to receiving water bodies. Erosion of P-laden soil is therefore more common on roads than in natural landscapes (Fu, et. al, 2010b, Larsen & Parks, 1997, Montgomery, 1994, Wemple & Jones, 2003). P concentration in the soil varies with land use patterns, but there are always natural levels of phosphorus present in the soil (Ishee, et. al, 2015). Excess suspended sediment in the water reduces sunlight infiltration and can reduce the productivity of aquatic ecosystems. P overload negatively impacts the natural functions of waterbodies by creating hypoxic conditions, killing off plant and animal life (Chen, et. al, 2019). A deeper understanding of the role of road networks in soluble phosphorus mobilization is necessary to inform remediation efforts in the future and help restore impaired waterways.

Literature Review

Water Quality and Phosphorus

Phosphorus and other nutrient input to lakes is associated with harmful algal blooms, eutrophication, reduction of biodiversity, and destruction of aquatic plant and animal habitats (Carpenter, 1998, USEPA, 2015). Eutrophication of lakes has direct and indirect effects on the many functions for which those lakes are used. Phosphorus is the limiting nutrient for the growth of cyanobacteria, the species that makes up most algal blooms, so increased phosphorus levels can increase the productivity of these harmful bacteria. The increasing frequency of algal blooms impairs freshwater ecosystem processes and the recreational and aesthetic values derived from rivers, lakes and coastal waters (USEPA, 2015, Charlier, et. al, 2008, Chen, et. al, 2019). Algal blooms negatively affect these functions by reducing sunlight infiltration, consuming vital nutrients, reducing dissolved oxygen levels, and producing harmful byproducts (Charlier, et. al, 2008, Chen, et. al, 2019). The mobilization of P and its deposition in lakes have been partially attributed to road networks (USEPA, 2015). This nonpoint source of phosphorus is difficult to quantify because of the wide affected area and the multitude of related nutrient sources. Much of the nonpoint P found is the water system can be attributed to urban and agricultural processes (Carpenter, 1998). By quantifying P runoff resulting from sediment mobilization, the erosive processes contributing to this issue can be more effectively addressed.

Road networks have the potential to drastically alter hydrologic processes including subsurface flow, stream sediment transport/deposition, stream connectivity, and chemical concentrations in the water (Amrhein, et. al, 1992, Araujo, et. al, 2014, Blanton & Marcus, 2009, Bracken & Croke, 2007, Drapper, et. al, 2000, Larsen & Parks, 1997, Negishi, et. al, 2008). Roads on slopes often intercept the water table and associated stream networks. These interactions with hydrologic processes mobilize surface sediment and nutrients, increasing the sediment load of adjoining streams with potentially harmful effects to the hydrology and ecology of the area (Ziegler, et. al, 2006). Roads also have the tendency to concentrate and mobilize sediment-bound nutrients and pollutants, especially in cases of heavy traffic or in areas with widespread agriculture, logging, and other industry (Amrhein, et. al, 1992, Drapper, et. al, 2000, Grayson, et. al, 1993, Kerri, et. al, 1985, Ramos Scharrón, 2012, Wemple, et. al, 2017). Incorporation of these additional contaminants and sediment show widespread effects on local ecology and water productivity. Phosphorus pollution has one of the highest impacts on water security and biodiversity of all water pollutants based on a cumulative threat framework for water for sources of water quality degradation (Vörösmarty, et. al, 2010).

Erosion Dynamics on Roads

Roads provide pathways for overland transport of anthropogenic and naturally-deposited sediments and nutrients through erosion (Fu, et. al, 2010b, Larsen & Parks, 1997, Montgomery, 1994, Wemple & Jones, 2003). Roads are far less permeable and often more erodible than surrounding natural soils, leading to surface flow during heavy rainstorms on the road surface and in constructed ditches and culverts (Wemple, et al, 2017). Extreme storms are expected to increase in frequency due to climate change, making the need to study the effects of these erosive events even more dire (Dore, 2005). Extreme road erosion can result in the degradation and destruction of engineered drainage systems and passable road surface, and can even prevent the use of heavily effected roads through mass wasting (Wemple, et. al, 2017). Road-derived erosional processes include the formation of roadside gullies, down-slope landslides, and surface channels within the road area (Montgomery, 1994, Takken, et. al, 2008). The erosive power of channeled water is intensified by the lack of vegetation on and around roads. The roots of natural vegetation hold surrounding sediment in place, reducing erosion. Tree canopies diffuse the kinetic energy of falling rain, reducing its erosive force. Vegetation is a powerful preventative measure against severe erosion (Castillo, et. al, 1997). Roads' tendency to erode is highly variable, and analysis of the many factors with potential to alter erosion is necessary for a comprehensive understanding of road erosion dynamics (Wemple, et al, 2017, Wemple & Jones, 2003, Ziegler, et. al, 2001a). Previous studies have related the magnitude of gully erosion to factors including drainage area size, slope angle, rainfall intensity, and flow discharge during storm events (Nachtergaele, et. al. 2002, Xu, et. al, 2017). These factors have been studied with methods including laboratory and open-air flume experiments, artificial rainfall simulations, field scans, and photogrammetry (Daba, et. al, 2003, Nachtergaele, et. al, 2002, Takken, et. al, 2008, Xu, et. al, 2017). The negative impacts of road erosion are reduced with the installation of proper runoff mitigation techniques that are designed to accommodate local topography, underlying material, weather patterns, drainage area, hydrologic connectivity, and level of existing erosive damage (Wong, et. al, 2000, Ziegler, et. al, 2006). Some of the Best Management Practices (BMPs) for prevention of road erosion include: water bars, stone revetments, vegetated buffers, and plunge pools (Garton, 2015). These structures constitute a subset of the solutions that can reduce the amount of soil mobilized by high flow events.

Phosphorus in the Soil

The soil mobilized by gully erosion from roads contains varying levels of phosphorus with natural and anthropogenic origin. The concentration of P in the soil depends primarily on surrounding land use (Ishee, et. al, 2015, Perillo, et. al, 2018). P concentrations tend to be highest in areas with agricultural activity, stemming from fertilizers and manure. Concentrations are often lower in areas further from developed land such as forests, where P exists in a (lower) natural abundance in the soil (Ishee, et. al, 2015). Vermont's land use patterns include wide swaths of both agricultural and forested areas, leading to high variability in soil P concentration across the state. Different depths in the soil profile also show variation in P concentration, with the highest concentrations usually found within the 15-30 cm closest to the surface. This higher concentration in topsoils stems from biological activity above the ground surface and in the organic and surface soil horizons (Ishee, et. al, 2015). These topsoils with the highest concentrations of P are the first to be mobilized during erosion, and are therefore quickly incorporated into downslope waterways. This process of soil mobilization adds excess suspended sediment and nutrients to the hydrologic system, resulting in water quality degradation in downstream waterbodies like rivers, oceans, and lakes.

Local Context: Vermont and Lake Champlain

Lake Champlain is situated between Vermont, New York, and Quebec. The lake is over 120 miles long and supports agriculture, industry, and recreation. The Champlain Basin has 7% of its area in Québec, 37% in New York, and 56% in Vermont, making Vermont its largest area of water contribution (USEPA, 2015). Vermont's land area is dominated by agricultural land use such as cropland, pasture, and livestock. Agricultural processes such as fertilization, manure spreading, livestock, pesticides, and crop irrigation serve to add excess nutrients to the environment and mobilize them through the water system (Carpenter, 1998). In 2015, the United States Environmental Protection Agency (EPA) produced an updated plan for a Total Maximum Daily Load (TMDL) of phosphorus that can enter Lake Champlain. In this report, the EPA requires that Lake Champlain remain suitable for the following purposes: aquatic biota, wildlife, aquatic habitat, aesthetics, public water supply, irrigation of crops, other agricultural uses, swimming, primary contact recreation, boating, fishing, and other recreational uses (USEPA, 2015). An EPA investigation between 2001 and 2010 estimated the yearly phosphorus input to be 922 metric tons, and this number has likely increased since. Seven percent of this P input is associated with wastewater, while ninety-three percent is associated with forests, developed land, agriculture, and unstable water corridors (USEPA, 2015). Road networks exacerbate stream corridors making them a contributor to the phosphorus budget. To protect the vital functions of the lake, scientists must further examine the negative contribution made by the transportation sector. It is critical that sediment-bound P transport from roads be quantified and addressed.

Motivation for the Study and Research Questions

The purpose of my thesis is to estimate the severity of gully erosion on roads across the state of Vermont. This thesis serves as a component of a study being conducted for the Vermont Agency of Transportation (VTRANS) by the University of Vermont. This ongoing study titled, *Quantifying Nutrient Pollution Reductions Achieved by Erosion Remediation Projects on Vermont's Roads,* provided the framework for this project's methods and goals. The 2-year VTRANS study will use collected field survey data and calculated geospatial statistics to synthesize a system to allocate state funds to erosion remediation projects based on their estimated reduction of phosphorus mobilization. The findings in this thesis will be one of many steps necessary for VTRANS to calculate P mobilization potential at different impaired sites and to understand the erosion dynamics that contribute to the problem.

This thesis addresses a subset of the goals of the VTRANS study since the timeframe falls only within the first year of the study. I use existing outfall inventories to analyze the magnitude of the issue and the steps needed to create more comprehensive datasets documenting road erosion. I use those same inventories with derived geographic data to determine the factors that increase the probability of gully erosion at concentrated outfalls from roads. I use high definition field surveys of individual erosion sites to inform my perspective on the erosion dynamics that contribute to the problem. I use soil phosphorus concentration data to make rough calculations describing the magnitude of nutrient mobilization occurring from gully erosion at individual sites and across broader areas. The goal of this thesis is to provide useful data and methods to the Vermont Agency of Transportation and their partners in their attempt to reduce harmful erosion on Vermont's roads.

Chapter 2: Quantifying and Predicting the Magnitude of Gully Erosion and its Contribution to Nutrient Pollution from Vermont's Roads

Introduction

The Earth's water is a limited and precious resource. Human industry, urban infrastructure, and agriculture threaten water quality by disrupting the water cycle and contributing excess pollutants, nutrients and sediments to the environment (USEPA, 2015, Vörösmarty, et. al, 2010). Nutrient pollution including nitrogen and phosphorus can seriously harm the natural functions of water bodies by promoting extreme algal growth leading to eutrophication and hypoxic conditions (Carpenter, 1998, USEPA, 2015). Road networks mobilize nutrients and sediment by concentrating surface water flow into erosive channels. By providing erodible channels, roads add additional nutrients to downstream waterways, leading to destruction of aquatic habitats (Fu, et. al, 2010b, Larsen, et. al, 1997, Montgomery, 1994, Wemple & Jones, 2003, Carpenter, 1998). Phosphorus, one of the nutrients that poses the greatest threat, exists in natural concentrations in soil. Areas dominated by agriculture tend to have greater P concentrations in the soil from fertilizer, manure, and other agricultural processes. Topsoils also tend to have higher P concentrations than soils lower in the vertical profile (USEPA, 2015, Ishee, et. al, 2015, Perillo, et. al, 2018). With its widespread agriculture, Vermont has the potential for serious nutrient pollution in its waterways.

With unpaved roads on steep slopes and periods of heavy precipitation, Vermont can have severe local erosion problems. Excess nutrients in the rivers and Lake Champlain have consistently spawned dangerous algal blooms that make the water unsuitable for recreation, industry, and agriculture. Lake Champlain spans nearly the entire Western border of Vermont and most of its watershed is within the borders of the state (USEPA, 2015). Persistent algal blooms in the lake have necessitated new legislation to limit nutrient pollution. The EPA produced new TMDL guidelines in 2015, which require the agricultural, industrial, and transportation sectors (among others) to quantify and reduce their nutrient contributions to the lake (USEPA, 2015). This study focuses on the transportation sector and its impacts on erosion dynamics and nutrient pollution.

The purpose of this study is to survey the magnitude of gully erosion at concentrated outfalls within Vermont's transportation network. This includes closed drainage systems in urban areas, and open drainage systems in rural Vermont. This study incorporates high resolution field data to illustrate the nuanced dynamics of road erosion along the spectrum of dirt roads to interstate highways. The goal of this investigation is to inform further efforts to reduce phosphorus runoff by providing a comprehensive picture of the problem Vermont faces.

Methodology

Study Area

This study is subdivided into three sections. The first section involves the collection of samples and surveys at eight study sites. These are all gullies at culvert outlets associated with Vermont's road network. Sites are on State and Municipal roads. State sites are all on Interstate Highway 89. Municipal sites are all on class three roads, except for Maple Run Lane in Stowe which is a class four road.

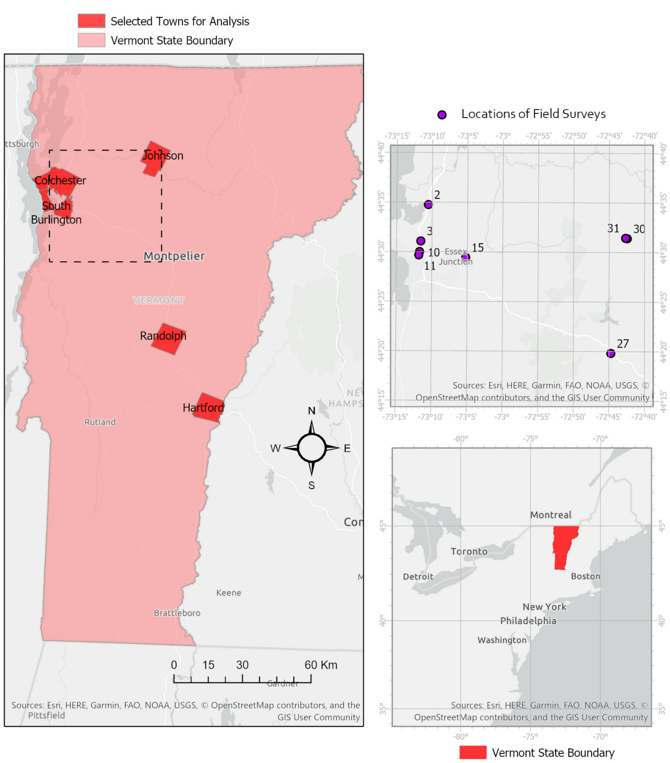


Figure 1: Map of study area. Vermont's location in the Northeast United States shown in the bottom right panel. Five towns of interest and the extent of the field sites are shown in the large panel on the left. Point locations of the field sites are shown in the top right panel.

These eight field sites are located within the Winooski and Lamoille river watersheds. Both rivers drain into Lake Champlain which is an impaired water body (USEPA, 2015, Wemple, et. al, 2017). The sites for this section of the project are generally in the northeast of the state of Vermont, with a range of distance from Lake Champlain (see dashed outline in left panel of Figure 1 for extent of field sites).

The second section of this study includes a statistical analysis of the factors contributing to erosion risk on Vermont's roads. This portion was completed using geographic and landscape data. This analysis was carried out using IBM's SPSS software as well as ArcGIS Pro. This analysis was based on all recorded culverts within Chittenden County.

The third section of this study uses Road Erosion Inventories (REI) collected by towns in compliance with the Municipal Roads General Permit (MRGP). This work was carried out using ESRI's ArcGIS Pro software. The analysis focuses on five Vermont towns: Colchester, Johnson, South Burlington, Randolph, and Hartford. These five study areas span a broad section of Vermont, as shown in the left panel of Figure 1. The selected towns constitute a range from urban to rural, with South Burlington, Hartford, and Colchester being more urban and Randolph and Johnson being more rural. The geospatial analysis applied to these areas is used to estimate the magnitude of the problem of gully erosion across the entire state. These five towns are not representative of the whole state, but incomplete datasets necessitated a choice of a small subset of towns for the analysis.

Field Site Selection

Potential field sites were identified by participating Regional Planning Commissioners, VTRANS representatives, and other community partners. Over 30 potential sites were inspected over the spring and summer of 2019. The site ID numbers used to differentiate the sites in this report reflect the initial larger sample size. Those chosen for the study were selected based on accessibility by vehicle, property-owner permission, and topography that was possible to survey with the terrestrial LiDAR scanner. Sites that had potential for remediation by town governments or VTRANS were also prioritized. It was important to include towns on both class 3 and class 4 roads as well as interstate highway 89. This made for a small dataset that covered some of the diversity in road types found across the state. The survey data produced during this study were provided to community partners to help inform remediation efforts.

LiDAR Surveys

Three-dimensional (3D) scans of gully sites were conducted using a RIEGL VZ-1000 terrestrial LiDAR scanner over the summer and fall of 2019. The workflow for each site was conducted using the following procedure: First the site was visually inspected to determine the number of scans necessary for total coverage the gully. The LiDAR scanner takes 360˚ panoramic scans from a fixed location, so complete coverage of a single gully required multiple scan locations. Planned scan locations were marked with tripods or stray branches. Incorporation of reflective tie points allowed overlay of separate scans into one digital elevation model. Tie point locations were decided with the following criteria in mind: (1) Each of the five tie points must be visible from each scan location, (2) The tie points should be at varying elevations on the surrounding slope, (3) The tie points should be at varying distances from the gully, (4) The tie points should generally surround the gully. Once the tie point locations were decided, four-foot segments of rebar were hammered into the ground at each tie point location. The rebar was left with between 4 and 6 inches of exposed metal above the surface. Each piece of rebar was flagged with high-visibility tape, and capped with a UVM survey cap. Next, 10 cm cylindrical reflectors were set up on level, 8-foot tripods directly above the rebar segments. These served as the tie points. LiDAR scans were then conducted from each of the selected scan locations, with visual inspection of the resulting point clouds in between each scan. Through these visual inspections, areas of low coverage were identified and further scan locations were adjusted to account for these areas. Repeat surveys of the same sites will reuse the same tie point locations for temporal comparison of the scans. Relative scan locations will be kept constant, with a higher priority on collecting data for the whole gully than maintaining the exact same scan locations.

Completed scans were processed into Digital Elevation Models by Emma Estabrook using the RIEGL software package, Civil 3D, and QT Modeler. These data products were used to estimate the total volume of eroded sediment for each of the sites. Volume estimates, bulk density values, and soil phosphorus concentrations were used to calculate the total mass of mobilized P per gully using:

$$M_P = V_G \times \rho_S \times C_P \quad (1)$$

Where M_P is the total mass of mobilized phosphorus, V_G is the volume of the gully, ρ_S is the average bulk density of the sediment, and C_P is the average P concentration in the sediment. The final calculations for each site are compiled in Table 3. Phosphorus concentrations represent the average weight in mg of P found in one kg of sediment. These concentrations were calculated by taking an average of the phosphorus concentrations by depth for each gully.

Soil Sample Collection

Soil samples were collected from each of the field sites after LiDAR surveying was complete. These samples were processed to determine phosphorus concentration and bulk density. Several soil samples were collected along the vertical profile of the gully wall. This provided separate samples for different soil depths. Total P and bulk density both vary along this profile (Ishee, E, et. al, 2015). Each soil sample was labelled with the site name and number, sample depth below the ground surface, and the date of sampling.

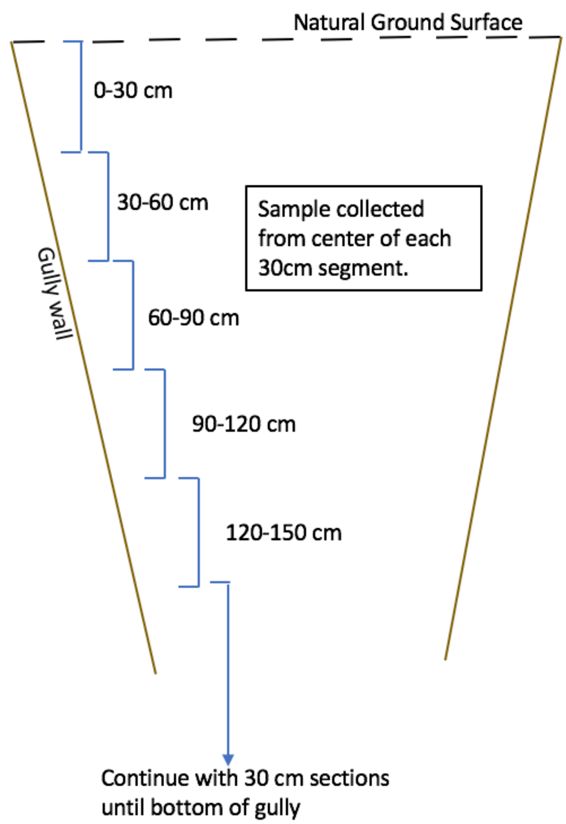


Figure 2: Diagram of the soil sampling method. Soil sampling design is based on consultation with Dr. Donald Ross from UVM Soil Science Department. Figure 2 represents a cross section of a gully.

Each soil sample had an exact volume of 90.59 cubic centimeters. The samples were collected using an AMS bulk density soil core sampler with a slide hammer attachment. This sampling process reduced compression of the samples to maintain natural soil density. Each sample was dried at 105 ˚C for 24 hours and weighed to calculate soil bulk density. This calculation included all sediment sizes in the samples, including coarse pebbles.

Nitric Acid Microwave Digest Procedure

All the soil samples were tested for phosphorus concentration. This required a laboratory digesting procedure (EPA method 3051A) to dissolve the P and make it available for analysis by the Inductively Coupled Plasma Atomic Emission Spectrophotometer (ICP). A nitric acid microwave digest procedure was conducted in the UVM Agricultural and Environmental Testing Laboratory to prepare the samples for this analysis.

Samples were prepared for digestion by collecting subsamples that were sieved to include only the fraction of sediment less than 2mm in diameter. The pebbles that made up a significant portion of the bulk densities of these samples were not included in this analysis. Roughly 2 grams of each subsample was then ground down to less than 1/2mm. At this size, the nitric acid digestion is effective.

For each round of the digest procedure, only 14 samples can be processed. One of these must be a nitric acid blank and another must be a reference soil. These are used for quality control purposes. There are 12 slots available for study samples, and at least two of them were duplicates for further quality control. Between 0.5 and 0.55 grams of each (<1/2mm) sample was weighed out. The weight of each was recorded, and then each sample was mixed with 10 mL of concentrated nitric acid. These were placed in Teflon tubes and run through a 30 minute HP500 cycle in a CEM Mars 5 Digestion Oven. After digestion, each sample was transferred into a test tube, and diluted with 0.1 molar nitric acid to a total of 50 mL per sample. These solutions were shaken and were then ready for processing in the ICP.

The ICP procedure was carried out by Dr. Donald Ross and Daniel Needham in the UVM Agricultural and Environmental Testing Lab, and produced values for P concentration in the samples in mg/L within the nitric acid solution. These values were converted to mg(P)/kg(soil) using the initial weight of soil that was used in each sample tube for the digest procedure.

GIS and Statistical Analysis of Gully Risk Factors

This analysis attempted to determine the factors that statistically contribute to a road segment's risk for gully erosion. This work was only done on all road segments within Chittenden County. The product was a statistical model that can be used to calculate the odds of gully erosion at individual concentrated outfalls. This equation was synthesized using the data outlined in Table 1.

Dataset or Layer	Type, Source
VT E911 Centerlines	Road segment centerline dataset, VCGI
VTCULVERTS	Vector Points, VTRANS
Surficial Geology	Surficial Geologic Material Distribution, VCGI
Soil Type	Soil Unit Distribution, VCGI
Land use/ Land cover	Raster (categorical), VCGI
10m LiDAR product	LiDAR tiles with 10m resolution, VCGI
Slope	Ground Slope (degrees), derived from LiDAR
Aspect	Slope Aspect (degrees), derived from LiDAR
Road Flow Accumulation	Road surface flow accumulation raster, Stone Environmental

Table 1: Data used in Gully erosion risk analysis. Data types and sources are included.

These data were manipulated in ArcGIS Pro to use SPSS to determine which of them significantly contributed to the odds of extreme erosion on the roads of Chittenden county. Data layers were clipped to the area of Chittenden county, and their coordinate systems were converted to NAD83 Vermont State Plane (meters). Slope and Aspect layers were derived from the original DEM using ArcGIS Pro's *slope* and *aspect* geoprocessing tools. VT Culverts points' *erosion* attribute was used to determine the levels of erosion at each culvert. The values for this field ranged from 0-4, with 4 indicating the lowest level of erosion and 1 indicating the highest level of erosion. Points with a value of 0 for the *erosion* attribute had unknown or unrecorded erosion severity. First, the points with *erosion* values of zero were removed from the dataset. The *erosion* attribute was recoded as a binary variable where the two higher *erosion* values were '1' and the lower values were '0'. The *Extract Multivalues to Points* tool was then used to give the remaining culvert points attributes for the associated values of all the raster datasets. This gave each VT Culvert point attributes describing the elevation, slope, aspect, flow accumulation, and land cover class. Next, the *Identity* tool was used to add surficial geologic material and soil type attributes to the points. The resulting attribute table for the edited VT Culvert dataset was then simplified through removal of unnecessary attributes, and exported as a comma separated value table for analysis in the IBM SPSS software.

In SPSS, the recoded binary *erosion* attribute was used as the dependent variable in a series of cross-tabulations and binary logistic regression analyses to determine the attributes that affected the odds of erosion among these data. Models with insignificant p-values and χ^2 or low model performance statistics were ignored (Agresti & Finlay, 1997). Once the most statistically significant and accurate equation was determined in SPSS, the ArcGIS Pro *Extract by Mask* tool was used to produce 10-meter resolution raster layers that only covered the road lines for Chittenden county. The *Raster Calculator* tool was used with the model equation to produce a raster with values equal to the *log*(odds of erosion). The same tool was then used again to convert log(odds) to odds using exponentiation. This value is expressed as a ratio of the odds that a gully will occur over the odds that the gully will not occur at a given raster pixel (Agresti & Finlay, 1997). This raster dataset can be used to calculate the odds of erosion at any outfall site on a road segment within Chittenden county.

GIS Analysis of Gully Frequency

Analysis of existing data was carried out using ArcGIS Pro to determine the frequency and general distribution of gullies within five selected Vermont towns. These data were collected by Regional Planning Commissions, Vermont Municipalities, and State agencies.

Dataset	**Source**
MRGP Road Erosion Inventory	Emily Schelley, VTDEC Stormwater Section
Chittenden County Road Erosion Inventory	Chris Dubin, CCRPC
VTCULVERTS Culvert Inventory	VT Agency of Transportation
Vermont state and town boundaries	VT Center for Geographic Information
Vermont Road Centerlines	VT Center for Geographic Information

Table 2: Datasets used for GIS frequency analysis and the people/agencies from which these data were obtained.

Five Vermont towns were chosen for GIS analysis based on data coverage within towns, desire for towns on a spectrum from rural to urban, and towns' location within the Lake Champlain basin. In each town, the total length of roads was calculated and compared with the total length of roads assessed for the MRGP. The number of gullies in each town was estimated twice: Once using the MRGP Road Erosion Inventory and once using the VT Culverts State Culvert Inventory.

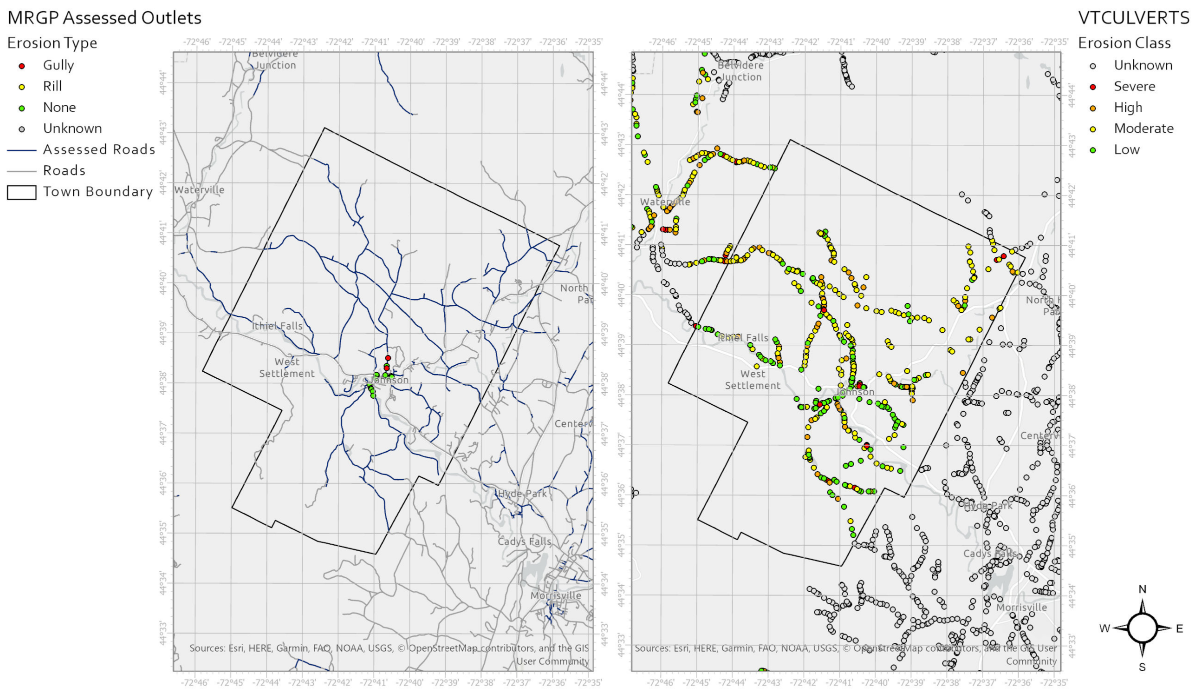


Figure 3: Data coverage for Johnson. MRGP REI data are shown in the left panel. VT Culverts data are shown on the right. Outfall points are color coded based on the *erosion* attributes from each dataset. The different meanings of this attribute in each dataset are shown in their respective legends. The road network for the MRGP data is color coded to show which segments have been assessed. Data coverage maps of the other four towns are in Appendix Figure A2.

From the REI, gullies were identified using the *DrainErosionValueID* data field, with a value of 1 indicating the presence of gully erosion at an outfall. In the VT Culverts dataset, gullies were identified using the *erosion* data field, with values of 1 or 2 indicating gully erosion (The classification of VT Culvert points as gullies is not explicit in the data and was assumed for processing purposes).

Using these classifications, the two different total numbers of gullies were calculated for each town to address the range in possible values. The total number of MRGP gullies in each town was estimated with:

$$N_g = [N_A/L_A] \times L_T \tag{2}$$

Where N_g is the estimate for total number of gullies, N_A is the number of assessed gullies, L_A is the length of assessed roads, and L_T is the total length of all roads. This calculation provided an estimate for the total number of MRGP outfalls with gully erosion problems. This number is doubtless an underestimate. It assumes that all culverts on all assessed road segments have been surveyed and recorded accurately.

Unlike the REI, the VT Culvert dataset has wide coverage in the state and includes location data for nearly all open-system culverts in the state. Unfortunately, the VT Culvert data only includes open-system drainage culverts, and does not have data on closed system outfalls like the REI. This shortcoming was partially addressed by estimating an adjusted total number of VT Culvert gullies with:

$$N_g = [N_S/N_A] \times N_N + N_S \tag{3}$$

Where N_g is the estimate for total number of gullies, N_S is the number of points classified with severe erosion, N_A is the total number of assessed culverts, N_N is the number of culvert points that have unknown erosion severity. These equations may have increased the accuracy of the estimates; but, they are still likely underestimations.

The estimates from each dataset were added together because they have negligible overlap, and are both assumed to be under-representative of the actual total number of gullies present within the five towns.

Results

Field Results

The field surveys at the eight study sites yielded LiDAR-derived digital elevation models (DEMs), soil bulk densities and P concentrations along the vertical profile of each gully. The gullies ranged in length from 20 meters to 53 meters, their volumes ranged from 4.6 m^3 to 197.8

m^3. The gullies ranged in maximum depth below the original ground surface from about 30 cm to 240 cm.

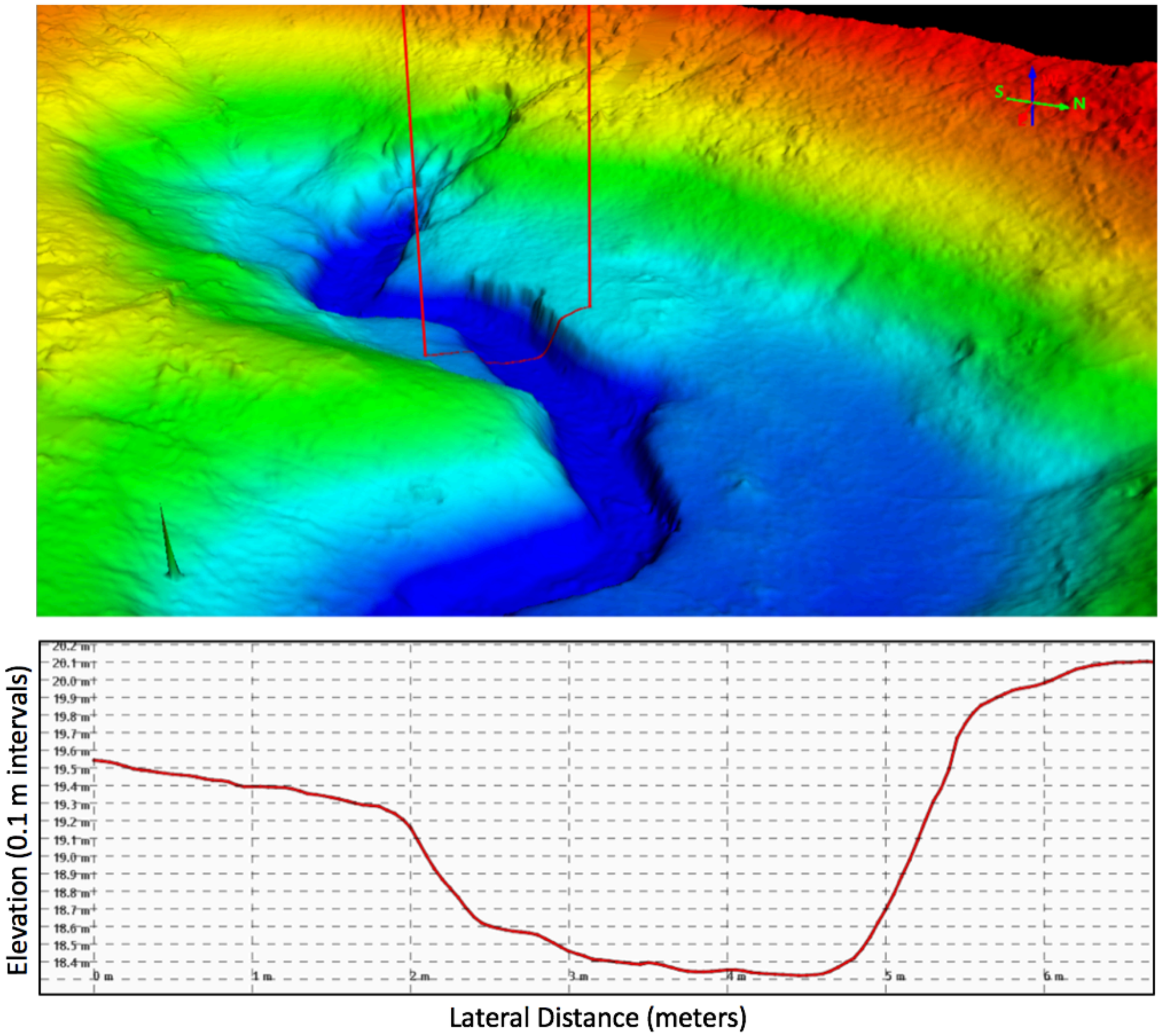
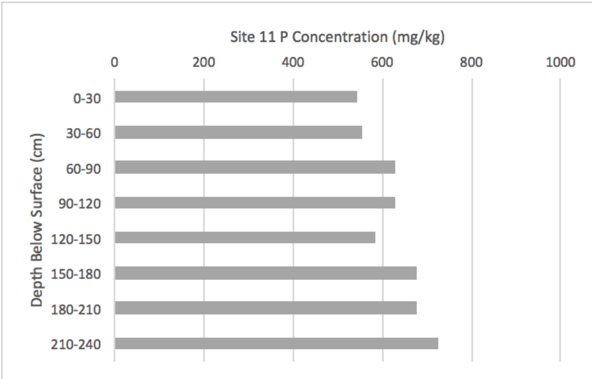
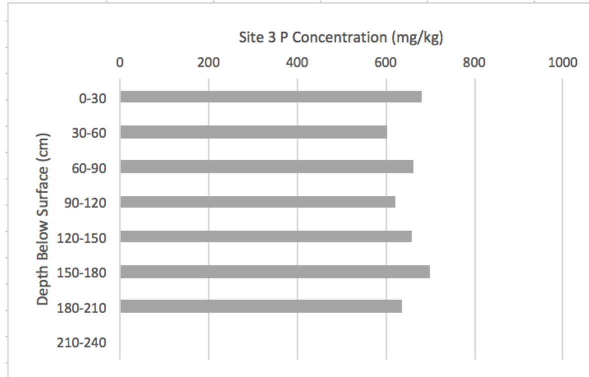


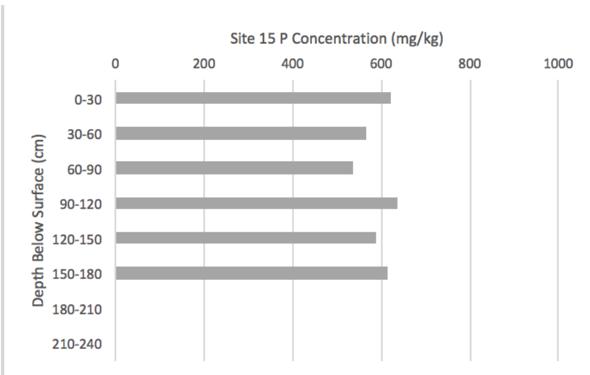
Figure 4: Digital elevation model for the bare Earth surface of site #2 on I-89 in Colchester. The scan was collected on 10/24/2019. The color ramp indicates elevation, with blue at the lower and red at the higher elevations. The cross-section profile provides a size scale in meters, and is displayed in the DEM image as the red line. The DEMs for the other seven sites are in Appendix Figure A1.

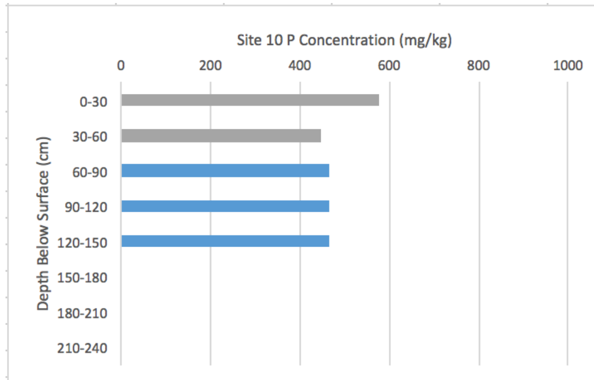
Soil bulk densities among the eight sites ranged from 0.75 g/cm^3 to 1.64 g/cm^3 with an average of 1.28 g/cm^3. There was no visible trend in soil bulk density between sites, but densities were generally higher in samples from deeper in the soil profile. Interestingly, site 3 included both the highest and the lowest bulk density measurements of all samples. The bulk densities of all collected soil samples are in Appendix Table A2.

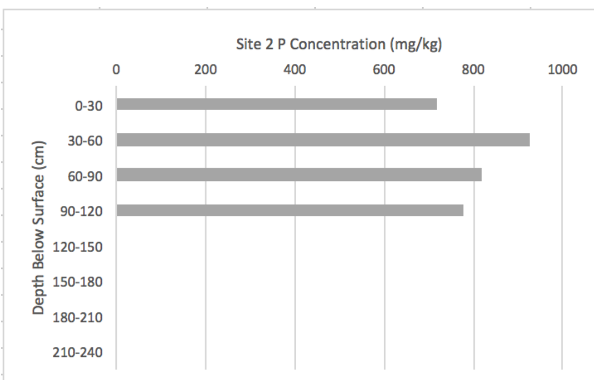
Individual phosphorus concentrations at different depths did not show as much variation as expected and did not follow a consistent trend. The sample P concentrations ranged from 448 mg/kg to 924 mg/kg and had an average of 625 mg/kg, with units in mg of phosphorus per kg of soil. Results from previous studies indicated that the graphs in Figure 5 (below) would show the highest P concentrations within the top soil layers, and lower concentrations from samples lower in the profile. This trend was not observed in any of these eight sites.

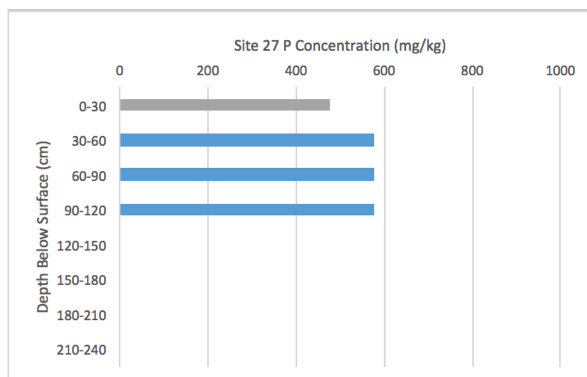

Site 11 P Concentration (mg/kg)
0 200 400 600 800 1000
Depth Below Surface (cm)
0-30
30-60
60-90
90-120
120-150
150-180
180-210
210-240

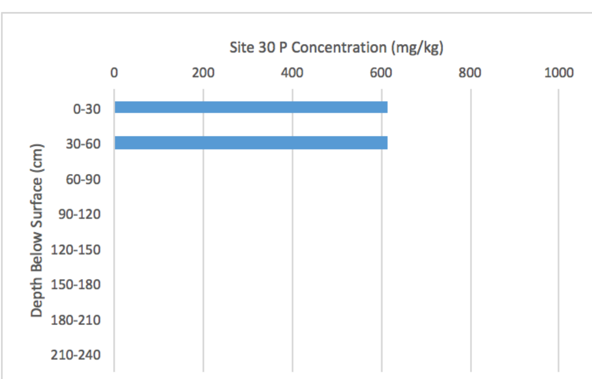

Site 3 P Concentration (mg/kg)
0 200 400 600 800 1000
Depth Below Surface (cm)
0-30
30-60
60-90
90-120
120-150
150-180
180-210
210-240


Site 15 P Concentration (mg/kg)
0 200 400 600 800 1000
Depth Below Surface (cm)
0-30
30-60
60-90
90-120
120-150
150-180
180-210
210-240


Site 10 P Concentration (mg/kg)
0 200 400 600 800 1000
Depth Below Surface (cm)
0-30
30-60
60-90
90-120
120-150
150-180
180-210
210-240


Site 2 P Concentration (mg/kg)
0 200 400 600 800 1000
Depth Below Surface (cm)
0-30
30-60
60-90
90-120
120-150
150-180
180-210
210-240


Site 27 P Concentration (mg/kg)
0 200 400 600 800 1000
Depth Below Surface (cm)
0-30
30-60
60-90
90-120
120-150
150-180
180-210
210-240


Site 30 P Concentration (mg/kg)
0 200 400 600 800 1000
Depth Below Surface (cm)
0-30
30-60
60-90
90-120
120-150
150-180
180-210
210-240

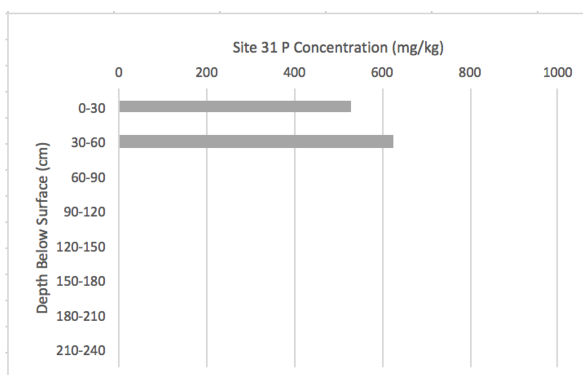

Site 31 P Concentration (mg/kg)
0 200 400 600 800 1000
Depth Below Surface (cm)
0-30
30-60
60-90
90-120
120-150
150-180
180-210
210-240

Figure 5: Phosphorus concentrations in the soil at each of the eight study sites. Concentrations are displayed along the vertical profile of the gully. Gullies varied in depth, so some do not have measurements that reach the maximum depth of all gullies in the study (240 cm). Some samples needed to be compiled so that all depths were processed before labs were shut down due to the current COVID-19 outbreak. Compiled samples are shown in blue.

The total estimated mobilized phosphorus per gully showed a wide range based mainly on the relative volumes of the gullies. The gullies showed a range between 2.5 kg to 196.3 kg of mobilized phosphorus. The average total mobilized P for these study sites was 81.5 kg.

Site Name (Site ID Number)	**Volume (m^3)**	**Average Phosphorus Concentration (mg/kg)**	**Average Bulk Density of Soil (g/cm^3)**	**Mobilized Phosphorus (kg)**
I89, Colchester (3)	146.1	652	1.14	108.8
I89 Colchester (2)	197.8	810	1.22	196.3
I89, Waterbury (27)	39.3	552	1.18	25.7
Young St, Colchester (10)	82.4	495	1.46	59.6
Elm St, Winooski (11)	162.4	628	1.43	146.0
Vale Dr, Essex (15)	34.2	593	1.36	27.6
Maple Run Ln, Stowe (30)	52.6	614	1.20	38.8
Maple Run Ln, Stowe (31)	4.6	578	0.95	2.5

Table 3: Calculated volume, P Concentration, Bulk Density and Mobilized P for each of the eight study sites. Volumes calculated from LiDAR-derived DEMs. P Concentration and Bulk Density represent averages for each gully and were quantified from analysis of the soil samples. Total mass of mobilized phosphorus was calculated using Equation 1.

Gully Erosion Risk Analysis

The tested explanatory models included three single-variable categorical models, four single-variable continuous models and four multi-variable mixed models. The results of these regression analyses are summarized in Table 4.

Model	**Type**	χ^2	**p**	**% Correctly Classified**	**Log Likelihood**
LULC (Land Use/ Land Cover)	Categorical	48.454	< 0.0005		
LITHCODE (Surficial Geology)	Categorical	63.263	< 0.0005		
MUKIND (Soil Type)	Categorical	12.726	0.002		
ASPECT	Continuous	1.474	0.225		
SLOPE	Continuous	65.021	< 0.0005	88.1	2311.8
ELEVATION	Continuous	61.703	< 0.0005	88.1	2315.1
FLOW ACCUMULATION	Continuous	0.547	0.459		
LITHCODE + SLOPE	mix	106.113	< 0.0005	88.1	2270.7
SLOPE + ELEVATION	**mix**	**96.206**	**< 0.0005**	**88.2**	**2280.6**
LITHCODE + ELEVATION	mix	93.149	< 0.0005	88.1	2283.7
LITHCODE + SLOPE + ELEVATION	mix	125.075	< 0.0005	88.1	2251.8

Table 4: Results of statistical analysis of culvert erosion vs independent variables, including variable types, chi-square test statistic, probability, and model performance statistics. The selected model including elevation and slope is highlighted in bold.

With insignificant p-values, soil type, aspect, and flow accumulation did not have a significant effect on the presence of erosion at a given site. All other factors had a significant effect on the dependent variable, but the best set of predictors of gully occurrence were the local ground slope and the elevation. These factors contributed most heavily to gully erosion risk among these data according to the following relationship:

$$log(\mathrm{P}) = -3.136 + 0.028(\mathrm{S}) + 0.001(\mathrm{E}) \quad (4)$$

Where P represents the ratio of the chance of gully erosion over the chance of no gully erosion at each outfall, S is the average ground slope within a 10-meter buffer around each outfall, and E is the elevation above sea level in meters of each outfall. This model correctly classified over 88% of the point occurrences as gullies.

Gully Erosion Frequency Analysis

The data used for the GIS analysis of gully distribution and frequency in selected towns showed incomplete coverage across the state of Vermont. This necessitated the use of equations 2 and 3 to calculate estimated numbers of gullies per town as outlined in Table 5.

Row #		**Johnson**	**Hartford**	**Randolph**	**Colchester**	**South Burlington**
1	Total road length (km)	144.6	375.9	232.3	284.8	209.1
2	MRGP assessed road length (km)	89.3	81.7	59.8	38.2	31.6
3	MRGP assessed road length (%)	62	22	26	13	15
4	MRGP outfalls (no) [1]	17	127	26	51	148
5	MRGP points classified as gullies (no)	2	25	6	9	37
6	MRGP gully frequency (no/km assessed road length)	0.02	0.31	0.10	0.24	1.17
7	Estimated gully total by town using MRGP dataset (no) [2]	3	115	23	67	245
8	VT Culverts (no)	383	1081	1027	188	340
9	VT Culverts assessed (no)	383	0	0	42	257
10	VT Culverts assessed and assumed gullies (no) [3]	61	n/a	n/a	6	25
11	VT Culverts not assessed and assumed gullies (no) [4]	0	*144*	*137*	21	8
12	Estimated gully total by town using VT Culverts (no) [5]	61	144	137	27	33

13	Estimated total gullies by town using MRGP and VT Culverts (no)	64	259	160	94	278

[1] Includes all points in the MRGP point dataset used in this analysis. One "Null" point in Hartford not included.

[2] Estimated as Total road length for each town (row 1), multiplied by MRGP gully frequency (row 6)

[3] Based on assumption that *erosion* attribute coded as 1 or 2 are gullies

[4] Assumed gullies (row 10) divided by total culverts assessed (row 9) applied to VT Culvert total (row 8). Values for Hartford and Randolph use mean of row10/row9 for other three towns applied to VT Culvert total.

[5] Sum of estimates from assessed and not assessed culverts (rows 10 and 11)

Table 5: Calculated statistics concerning gully frequency within each of the selected towns. Estimates were calculated using Equation 3 and Equation 4. Values of zero indicate complete data with missing attribute values. Values of n/a indicate no data.

Total gully estimates per town from the MRGP data ranged from 3 to 245 gullies. The estimates from the VT Culverts data ranged from 33 to 144. The estimates compiled from both datasets ranged from 64 to 278. This wide range illustrates the differences in erosion severity that occur in separate geographic areas.

The incomplete data used in this analysis are not representative of the total number of gully erosion sites per town. However, they can be used to gauge a rough estimate of the total amount of phosphorus mobilized by gully erosion in each town. This provides an estimate of which towns are contributing the most and the least phosphorus.

Town	Total Gully Estimate (both datasets)	Average mobilized P per gully (kg)	Estimated Mobilized P per town (kg)
Johnson	64	81.5	5,216
Hartford	259	81.5	21,109
Colchester	94	81.5	7,661
Randolph	160	81.5	13,040
South Burlington	278	81.5	22,657

Table 6: Hypothetical total mobilized P per town. Total gully estimate represents addition of MRGP and VT Culverts estimates. Average Mobilized P is an average of the total mobilized P in the field sites.

The total estimated mobilized phosphorus per town ranged from 5,216 kg in Johnson to 22,657 kg in South Burlington. The average total mass of mobilized P among these five towns was 13,937 kg. These values show mobilized P over the course of the lifetimes of all assessed gullies within each town.

Discussion

These findings build on the conclusions of Croke & Mockler, 2001, Ramos Scharrón, 2012, Sidle & Ziegler, 2012, Takken, et. al. 2008, Wemple, et. al. 2017, Wemple & Jones, 2003, and other researchers in this field. It reinforces the scientific understanding that road drainage infrastructure poses a threat to water quality through sediment and nutrient mobilization at erosive sites. Results show that local slope and elevation have a significant effect on the probability that a given drainage feature will fail and cause severe erosion. Furthermore, this study summarizes the frequency and distribution of assessed gully erosion sites in Vermont.

The gully frequency analysis among the five study towns showed some interesting summary statistics. It shows that gully erosion from concentrated outfalls on roads has the potential to mobilize multiple tons of phosphorus in each of only five Vermont towns. With a conservative estimate of a 20-year total timeframe, these towns mobilize between 261 and 1,133 kilograms of sediment-bound phosphorus every year. This would make 697 kg/year the average per town, and there are 145 Vermont towns in the Lake Champlain Basin. These calculations would indicate that Vermont's road networks are contributing 101 metric tons of P to the lake every year, which would mean that the transportation sector is contributing nearly 11% of the lake's total phosphorus from gully erosion alone. These estimates are very rough, but they highlight how serious this issue is.

These estimates were calculated from the values in Table 6, which contain only hypothetical total mobilized phosphorus values per town. The timeframe of mobilization is unknown. This mass of phosphorus has been mobilized over the lifespan of each gully in the town which is not quantifiable. The average P per gully is based on a very small sample (8 gullies), and the total gully counts per town are under-representative. Legislative measures like the TMDL are necessary to slow the nutrient pollution that is plaguing Vermont's hydrologic system. A deeper understanding of the processes contributing to phosphorus mobilization is crucial as we move forward to a cleaner and healthier Lake Champlain.

The 8 field sites provided a focused look at the erosion dynamics occurring at concentrated outfalls on Vermont's roads. These high-resolution data give a comprehensive picture of the status of these sites, which can be used to inform further studies of these processes. The higher eroded volumes tended to be on steeper slopes and on looser material. The higher P concentrations were found at sites generally closer to Lake Champlain, which could be because they are receiving runoff from a larger geographic area that includes more agriculture. The average bulk density for the sites seems to follow a trend based on the urban or rural setting of the site. This observation comes with the caveat that some of these sites (especially along the highway) are within fill material that was not naturally deposited. Average bulk densities at Young Street, Vale Drive, and Elm Street were the highest. These were all in urban or suburban neighborhoods. The other sites were all in forested areas, either next to the interstate or on Maple Run Lane. This trend could reflect sediment compaction by urban processes.

The phosphorus concentration data by depth in this study did not align with the findings of Ishee, et. al. 2015, who highlights a body of evidence that P concentration will be highest at the surface and decrease downward. That evidence is based on trends of bioavailable phosphorus, and this study quantified total phosphorus. This study also includes erosive sites in fill material that was placed during road construction. This means that the concentration trend found in naturally-occurring soils will not necessarily be observed in these sites.

The eight surveyed gullies show a range from 2.5kg to nearly 200kg of mobilized phosphorus per gully. This study was unable to apply a timeframe to the mobilization process. However, when a single gully can mobilize hundreds of kilograms of sediment in its lifetime, and there are hundreds of gullies in each Vermont town, the mobilized sediment-bound P adds up to multiple tons from the transportation sector. These findings can provide valuable insight into fund allocation for repairs to these sites and others like them as Vermont attempts to address this widespread issue.

The statistical erosion risk analysis produced convoluted results. The equation was not effectively applied to a geospatial dataset for visualization. These results could have been more straightforward if the calculated probabilities were applied to the VT Culvert point data. Points would have probability values based on the pixel they inhabit and local probabilities would be more accurate to their specific points.

The estimates in Table 5 for gully numbers based on the MRGP data ranged from about 3 gullies in Johnson to 245 gullies in South Burlington. The low value in rural Johnson is likely a result of under-reporting of gully erosion on assessed roads outside of the town center, leading to a skewed value for the initial gully count. Conversely, South Burlington is a more urban setting where gully erosion is noticed and reported, leading to a larger sample size. Hartford and Colchester had estimated numbers of 115 and 67 respectively. Both towns are more urban than Johnson and Randolph. The trend of more gully erosion in urban settings than in rural ones could be a product of incomplete data, and does not represent the actual gully erosion distribution associated with differing land cover.

The VT Culverts dataset showed similarly unreliable coverage in these towns. Town estimates ranged from 27 in Colchester to 144 in Hartford. The towns with a value of n/a for row #10 in Table 5 had location data for culverts but had a value of 'unknown' for their *erosion* attribute. This could be a result of surveyor omission of this data field. The two towns without any inspected VT Culverts points have estimates based on the average ratio of inspected sites to gully sites from the other three towns. All the 383 points in the town of Johnson were assessed. The VT Culverts layer focuses on open-system drainage culverts, and Johnson is sparsely populated with little urban space in need of closed-system drainage features. There are likely very few closed-system drainages in Johnson, meaning that the VT Culverts data can represent a more robust sample of the drainage systems present in the town.

This study sheds light on the benefits and issues with state and municipal data collection on roads. When collected properly, these data can provide nuanced insights into the hydrologic and erosive effects of road networks. These inventories help keep communities informed of where their erosion issues are, and how best to use funds to fix their road problems. Without more data like these, it will be very difficult for Vermont to effectively limit phosphorus input to Lake Champlain. These data are not sufficient in their current state. There are wide areas with no MRGP inventory points at all. Surveyors can easily skew volume estimates for gully erosion by using the wrong units when entering measurements in the MRGP survey app. The surveyed points in this dataset prioritize locations that are already failing to meet standards, and so it does not constitute a representative sample of the outfalls in the state.

These inventories were not designed for the kind of analysis attempted in this study, and it is unfair to expect these sweeping changes immediately. If analyzing trends in gully erosion from concentrated outfalls is a priority for town and state governments, they should work toward broadening the surveying effort, and try to achieve more uniform data coverage. This recommendation can also be applied to the VT Culverts inventory. With so many unknown points, it is difficult to tell if statistical findings are truly accurate. It is possible that the identified erosion risk relationship would be different if more complete data were used for its generation.

This study constitutes a first attempt to estimate the severity of gully erosion from concentrated outfalls on roads across the state of Vermont and to determine the factors that contribute to this issue. The findings are mostly rough estimates, but can inform further studies about the difficulties of working with these kinds of data. Further surveys of outfall sites would help make a more useful erosion inventory for subsequent studies. The erosion issue cannot be solved until we have a better understanding of the magnitude of the problem.

There are several questions left unanswered by this study. What is the true magnitude of gully erosion in Vermont? On what timeframe do these gullies add phosphorus to the hydrologic system? Do the factors that affect erosion in Chittenden County apply to the rest of the state? Are there statistically significant factors that were overlooked in this study? What percent of sediment-bound phosphorus is accessible to aquatic biota? What percent of Lake Champlain's phosphorus budget is attributable to the transportation system? Each of these questions warrants another scientific study. A first step would be long-term documentation of gully evolution in the field. The sites in this study will be monitored for at least another year by VTRANS and their partners at UVM. By extending that timeframe, we could better understand the speed of development of these gullies. Additionally, studying outfall sites that are not actively eroding would provide a deeper understanding of the issue. This would also allow the possibility of documenting gully initiation as a site deteriorates. Widening the scope of the field surveys would give researchers a more representative sample of gully sites and provide data for more accurate estimations of average mobilized phosphorus. With this small sample size of field sites, statistical claims cannot be made. Further studies should incorporate enough sites to run summary statistical analyses. This study can provide a blueprint moving forward. With more studies of this kind, Vermont can better address the nutrient pollution from its transportation network.

Chapter 3: Implications and Reflection

Implications

There is still work to be done before we can deeply understand the severity and the drivers of gully erosion at concentrated outfalls on Vermont's roads. My work has simply consolidated the existing data and attempted to identify trends and key statistics. I hope that this study can help state legislators see that this issue cannot be ignored. Repairing the damaged sites is a necessary first step to reducing the transportation sector's continuing phosphorus mobilization. However, we must conduct studies to determine the efficacy of these repairs so that they are financially and environmentally beneficial. VTRANS and its partners are doing essential work to quantify the relative P reduction potentials of different BMPs. The state's dedication to fixing this problem is clear, but I think that more resources need to flow into programs like the MRGP. This could include focused training of surveyors to ensure that they are collecting standardized data for each outfall. The length, width and depth data in the road erosion inventories would benefit from standardization. If analysts were confident with these measurements, statistical analyses like those in this thesis would be much stronger. Planning commissions could also analyze the existing data and determine which entries need to be replaced due to inaccuracies and inconsistencies. By creating comprehensive surveys of the erosion happening on Vermont's roads, policy makers could make well-informed decisions about fund allocation. If a certain area poses a higher threat of P mobilization, repairs in that area could be prioritized. We must shift the solution away from responding to issues as they arise, and strive to mitigate erosion before it begins. None of this will be possible without a dedicated effort to accurately map the culverts and outfalls with and without gully erosion. The MRGP's system of assessing sites that do not meet regulations helps locate areas of concern, but it does not highlight places where structures are working well. Understanding what works is as important as understanding where the issues arise. With proper surveying of all drainage systems in the state, VTRANS would be well prepared to address problematic road erosion.

I realize that this is not a realistic achievement right now. To conduct surveys of this magnitude would be highly expensive for communities that do not have excess funding. State and federal funds would be necessary to produce complete and accurate data for the entire state.

The best choice right now is to repair roads with long-lasting BMPs that will prevent or reduce nutrient runoff for years to come. This will afford VTRANS and Vermont's towns time to rethink their transportation drainage infrastructure, and align it with the natural functions of the water cycle.

Reflection

The scope of this project has shifted and evolved over the last year. It has been an adventure to work with so many community partners and UVM faculty members. When I first began working on this project in the summer of 2019, the production of a thesis was a far-off, abstract concept. I threw myself into the work at hand, inspecting gully sites and beginning to learn how to use the Emlid GPS systems and the terrestrial LiDAR scanner, not really knowing how I would synthesize these data into a cohesive thesis. Thanks to the support of UVM professors and the VTRANS Technical Advisory Committee, I focused in on a product. My main objective was to contribute to their efforts in a meaningful way. I have grown academically and professionally by working to adapt to differing concerns and ideas about my methods and conclusions. It has been a challenge to get past obstacles like rain, snow, lack of data, and worldwide pandemics. By remaining committed to my central goal, I have written a thesis that brings me pride.

The senior thesis was not appealing to me for much of my college career. I thought of it as an unnecessary burden for one's final year in college. Having now undertaken this challenge, I disagree with my previous conclusion. This thesis has given me a chance to explore my relationship with academia, and picture myself as a contributor to real scientific innovation. It has kept me motivated to learn after having completed most of my other college requirements. This project helped me get a sense of professional work in environmental science, and has certainly informed my post-graduation goals. I am immensely grateful for the opportunity to write a thesis in the Department of Geography, a field of study in which I had little prior experience. I got to engage with new material throughout this process, keeping me interested and excited to continue. This project has solidified my motivation to continue working in the environmental field.

The personal and academic knowledge I have gained from this process will stay with me for my whole life. I can't imagine a better way to conclude my college career than to work so hard at a project and see it through to the end. I have proven to myself that I can accomplish my goals by staying motivated and falling back on my supportive mentors when I reach a seemingly insurmountable obstacle. As I embark into the next stage of my intellectual career, I will keep this knowledge close at hand.

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Works Cited

Agresti, A. & Finlay, B, (1997). Statistical Methods for the Social Sciences: Third Edition. Prentice Hall, 575-585.

Amrhein, C, Strong, J. E & Mosher, P. A. (1992). Effect of deicing salts on metal and organic matter mobilization in roadside soils. Environmental Science and Technology, 26, 703–709.

Anderson, D. M & MacDonald, L. H. (1998). Modelling road surface sediment production using a vector geographic information system. Earth Surface Processes and Landforms, 23, 95–107.

Araujo, H. A, Page, A, Cooper, A. B, Venditti, J, MacIsaac, E, Hassan, M. A & Knowler, D. (2014). Modelling changes in suspended sediment from forest road surfaces in a coastal watershed of British Columbia. Hydrological Processes, 28, 4914–4927.

Blanton, P & Marcus, W. (2009). Railroads, roads and lateral disconnection in the river landscapes of the continental United States. Geomorphology, 112, 212–227.

Boulton, A. J, Findlay, S, Marmonier, P, Stanley, E. H & Valett, H. M. (1998). The functional significance of the hyporheic zone in streams and rivers. Annual Review of Ecology and Systematics, 29, 59–81.

Bracken, L & Croke, J. (2007). The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. Hydrological Processes, 21, 1749–1763.

Carpenter, S. R, Caraco, N.F, Correl, D. L, Howarth, R.W, Sharpley, A. N & Smith, V. H. (1998). Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. Ecological Applications, 8(3), 559-568.

Castillo, V. M, Martinez-Mena, M & Albaladejo, J. (1997). Runoff and soil loss response to vegetation removal in a semiarid environment. Soil Science Society of America Journal, 61, 1116–1121.

Charlier, R, Morand, P, Finkl, C, (2008). How Brittany and Florida coasts cope with green tides. International Journal of Environmental Studies.

Chen, L, Delatolla, R, D'Aoust, P. M, et al. (2019). Hypoxic conditions in stormwater retention ponds: potential for hydrogen sulfide emission. Environmental Technology.

Croke, J & Mockler, S. (2001). Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. Earth Surface Processes and Landforms, 26, 205–217.

Daba S, Rieger W, Strauss P. 2003. Assessment of gully erosion in eastern Ethiopia using photogrammetric techniques. CATENA, **50**: 273-291. DOI: https://doi.org/10.1016/S0341-8162(02)00135-2.

Dore, M. H. I. (2005). Climate change and changes in global precipitation patterns: What do we know? Environment International, 31(8), 1167–1181.

Drapper, D, Tomlinson, R & Williams, P. (2000). Pollutant concentrations in road runoff: Southeast Queensland case study. Journal of Environmental Engineering, 126, 313–320.

Garton, Joanne S, "Master's Project: Evaluating the Effectiveness of Best Management Practices on Rural Backroads of Vermont: A Retrospective Assessment and Cost Analysis" (2015). *Rubenstein School Masters Project Publications*. 3. https://scholarworks.uvm.edu/rsmpp/3

Grayson, R. B, Haydon, S. R, Jayasuriya, M. D. A & Enlayson, B. C. (1993). Water quality in mountain ash forests-separating the impacts of roads from those of logging operations. Journal of Hydrology, 150, 459–480.

Ishee, E, Ross, D, Garvey, K, et. al. (2015). Phosphorus Characterization and Contribution from Eroding Streambank Soils of Vermont's Lake Champlain Basin. Journal of Environmental Quality, 44, 1745-1753.

Kerri, K. D, Racin, J. A & Howell, R. B. (1985). Forecasting pollutant loads from highway run off. Transportation Research Record: Journal of the Transportation Research Board, 1017, 39–46.

King, J. G & Tennyson, L. C. (1984). Alteration of streamflow characteristics following road construction in north central Idaho. Water Resources Research, 20, 1159–1163.

Fu, B, Lachlan, T, Newham, H & Ramos, S. C. (2010b). A review of surface erosion and sediment delivery models for unsealed roads. Environmental Modelling and Software, 25, 1–14.

Gucinski, H, Furniss, M. J, Ziemer, R. R & Brookes, M. H. (2001). Forest roads: A synthesis of scientific information. General Technical Report PNW- GTR-509. US Department of Agriculture Forest Service, Pacific Northwest Research Station: Portland, OR.

Larsen, M. C & Parks, J. E. (1997). How wide is a road? The association of roads and mass wasting in a forested montane environment. Earth Surface Processes and Landforms, 22, 835–848.

Luce, C. H. (2002). Hydrological processes and pathways affected by forest roads: What do we still need to learn? Hydrological Processes, 16, 2901– 2904.

McGrew, J. C, Lembo, A. J, et. al. (2014). An Introduction to Statistical Problem Solving in Geography. Waveland Press, 3.

Montgomery, D. R. (1994). Road surface drainage, channel initiation, and slope instability. Water Resources Research, 30, 1925–1932.

Nachtergaele J, Poesen J, Sidorchuk A, Torri D. (2002). Prediction of concentrated flow width in ephemeral gully channels. Hydrological Processes, **16**: 1935-1953. DOI: doi:10.1002/hyp.392.

Negishi, J. N, Sidle, R. C, Ziegler, A. D, Noguchi, S & Nik, A. R. (2008). Contribution of intercepted subsurface flow to road runoff and sediment transport in a logging-disturbed tropical catchment. Earth Surface Processes and Landforms, 33, 1174–1191.

Perillo, V, Ross, D, Wemple, B, et. al. (2018). Stream Corridor Soil Phosphorus Availability in a Forested-Agricultural Mixed Land Use Watershed. Journal of Environmental Quality, 48, 185-192.

Ramos Scharrón, C. E. (2012). Effectiveness of drainage improvements in reducing sediment production rates from an unpaved road. Journal of Soil and Water Conservation, 67, 87–100.

Ross, D.S, B.C. Wemple, L.J. Willson, C. Balling, K.L. Underwood, and S.D. Hamshaw. (2019). Impact of an extreme storm event on river corridor bank erosion and phosphorus mobilization in a mountainous watershed in the northeastern USA. J. Geophys. Res, Biogeosciences 124. doi: 10.1029/2018JG004497

Sidle, R. C & Ziegler, A. D. (2012). The dilemma of mountain roads. Nature Geoscience, 5, 437–438.

Takken, I, Croke, J & Lane, P. (2008). Thresholds for channel initiation at road drain outlets. Catena, 75, 257–267.

USEPA USEPA. (2015). Phosphorus TMDLs for Vermont Segments of Lake Champlain.

Vörösmarty, C. J, P. B. McIntyre, M. O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, et al. (2010). Global Threats to Human Water Security and River Biodiversity. *Nature* 467, 555–61. doi:10.1038/nature09440.

Wemple, B. C, Browning T, Ziegler AD, et. al. (2017). Ecohydrological disturbances associated with roads: Current knowledge, research needs, and management concerns with reference to the tropics. Ecohydrology.

Wemple, B. C, Clark, G, Ross, D, Rizzo, D. (2017). Identifying the spatial pattern and importance of hydro-geomorphic drainage impairments on unpaved roads in the northeastern USA. Earth Surface Processes and Landforms.

Wemple, B. C & Jones, J. A. (2003). Runoff production on forest roads in a steep, mountain catchment. Water Resources Research, 39, 1220.

Withers, P. J. A, Jarvie, H. P, Hodgkinson, R. A, Palmer-Felgate, E. J, Bates, A, Neal, M, ... Wickham, H. D. (2009). Characterization of phosphorus sources in rural watersheds. Journal of Environmental Quality, 38, 1998–2011.

Wong, T, Breen, P, Lloyd, S. (2000). Water sensitive road design: Design options for improving stormwater quality of road runoff. Cooperative Center for Catchment Hydrology, Technical Report 00/1. 83 pages.

Xu X, Zheng F, Wilson GV, Wu M. (2017). Upslope inflow, hillslope gradient and rainfall intensity impacts on ephemeral gully erosion.
Land Degradation & Development, **28**: 2623-2635. DOI: doi:10.1002/ldr.2825.

Ziegler, A. D, Negishi, J. N, Sidle, R. C, Preechapanya, P, Sutherland, R. A, Giambelluca, T. W & Jaiaree, S. (2006). Reduction of stream suspended sediment concentration by a riparian buffer: Filtering of road runoff. Journal of Environmental Quality, 35, 151–162.

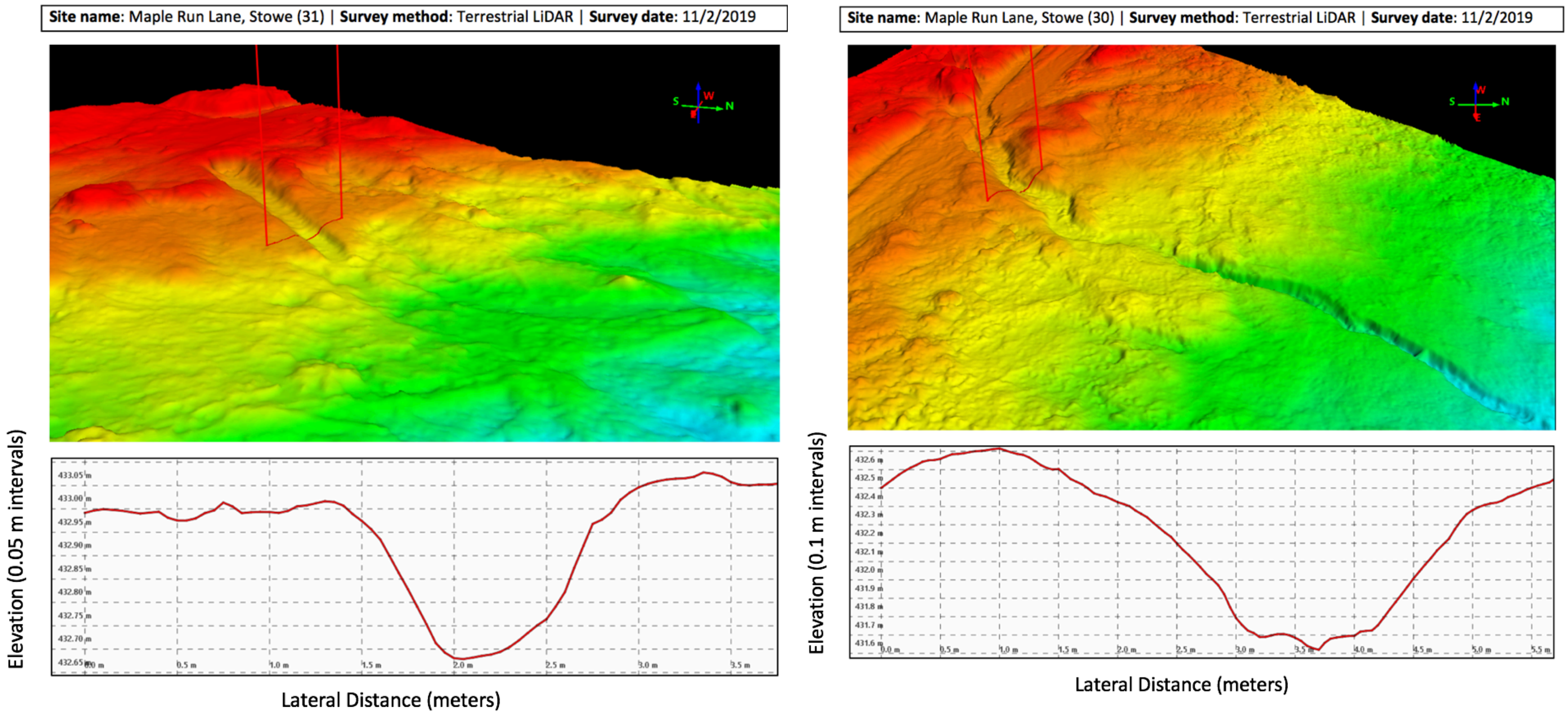
Ziegler, A. D, Sutherland, R. A & Giambelluca, T. W. (2001a). Interstorm surface preparation and sediment detachment by vehicle traffic on unpaved mountain roads. Earth Surface Processes and Landforms, 26, 235–250

Appendices

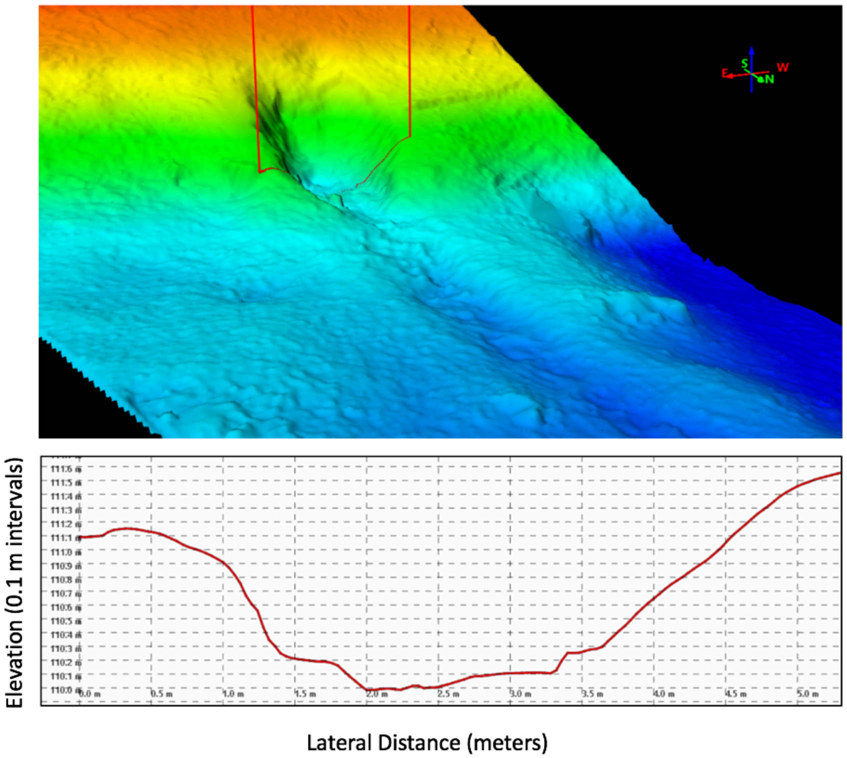
Table A1: Summary of gully dimensions. Length is the length of gully within the area of interest for volume estimations. Units reported in metric. Measurements calculated from DEMs derived from LiDAR scans.

Site name (Site ID Number)	Mean width (m)	Mean depth (m)	Length (m)	Volume estimate (m^3)	Notes
I89, Colchester (3)	4.3	1.5	39.2	220.4	
I89 Colchester (2)	3.3	1.3	36.7	261.9	Data needs to be corrected by 5.8 centimeters to account for water depth in gully
I89, Waterbury (27)	4.1	1.3	26.3	47.3	Dimensions include slump that is upslope from outfall
Young St, Colchester (10)	5.4	1.2	23.7	108.6, 106.4	
Elm St, Winooski (11)	5.3	3.0	26.3	229.4, 234.6	
Vale Dr, Essex (15)	4.2	0.9	19.3	41.2	
Maple Run Ln, Stowe (30)	2.8	0.6	52.7	59.7	Data needs to be corrected by 9.14 centimeters to account for water depth in gully
Maple Run Ln, Stowe (31)	1.4	0.2	28.0	8.1	Data needs to be corrected by 5.9 centimeters to account for water depth in gully.

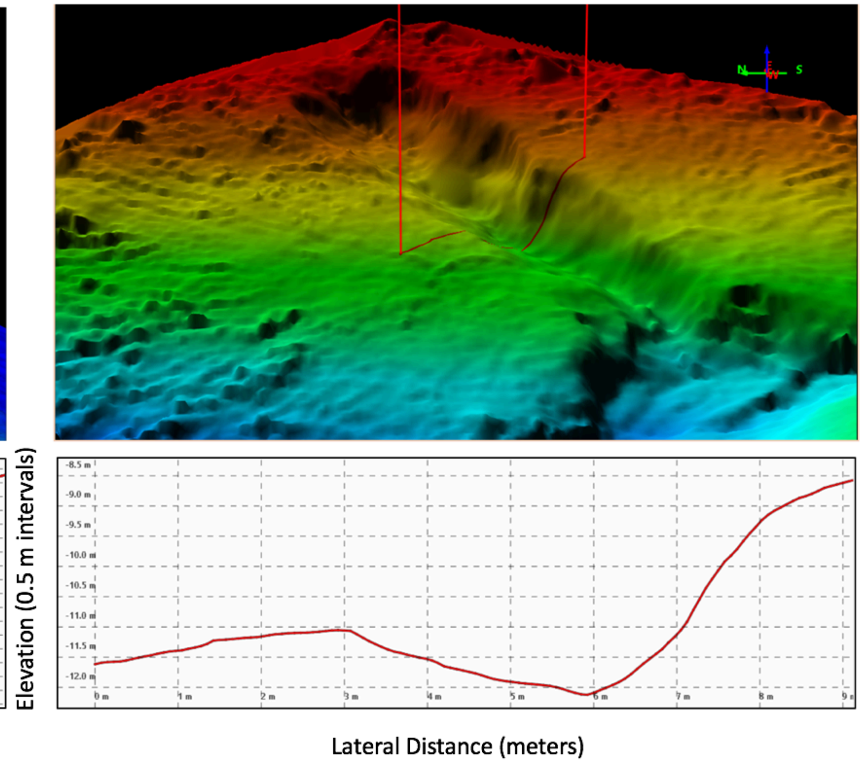
Figure A1: (7 panels) Derived DEMs for the remaining seven field sites. Each panel includes site name and number, survey method, and the date that the scans were collected. Elevation is symbolized with blue-red color ramp. Cross sections indicated with red lines have units in meters for scale.



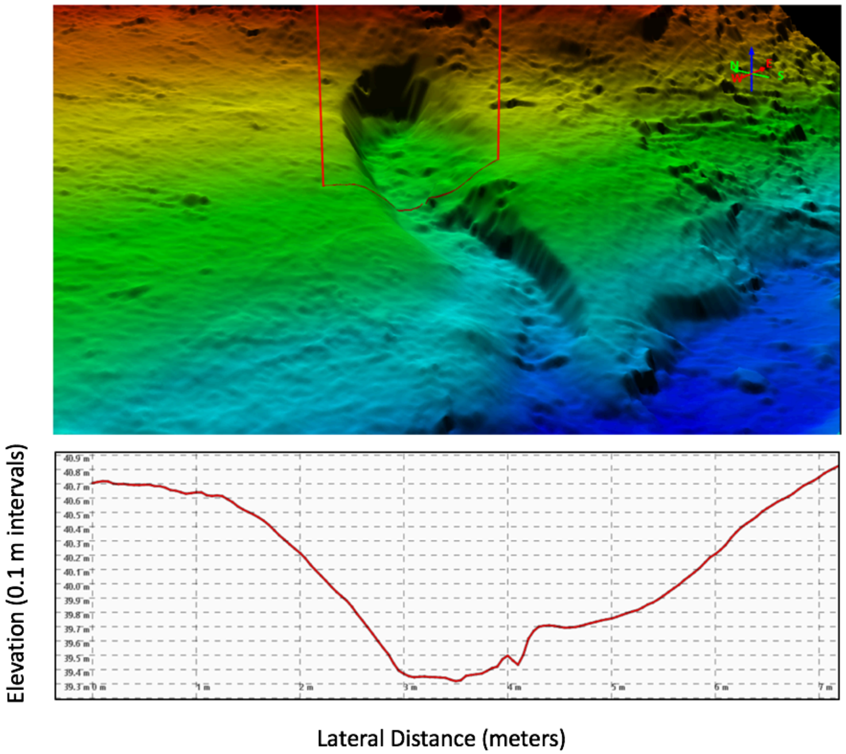
Site name: Vale Drive, Essex (15) | **Survey method**: Terrestrial LiDAR | **Survey date**: 9/27/2019



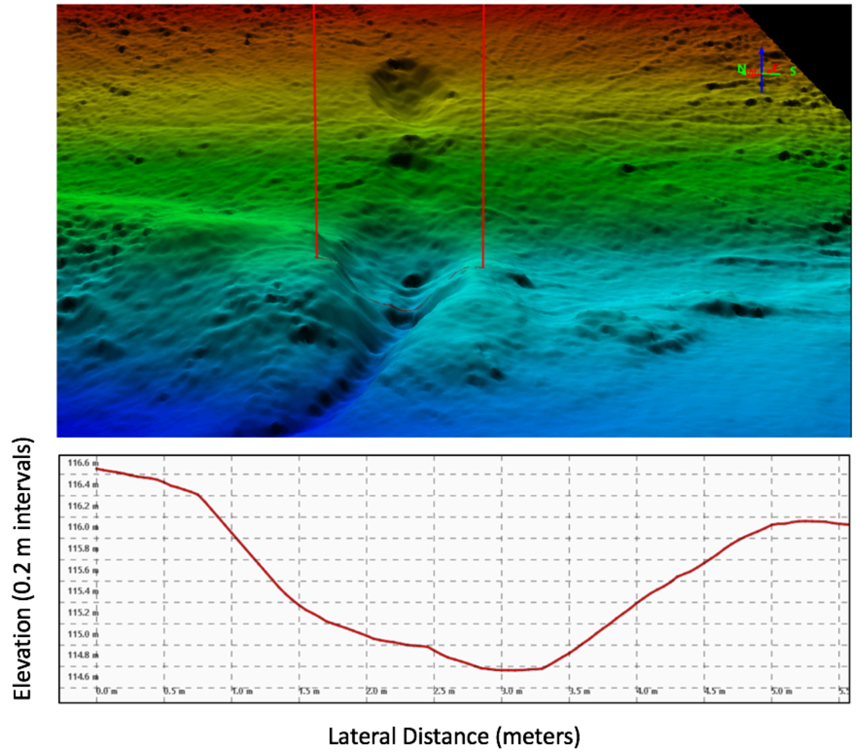
Site name: Elm St, Winooski (11) | **Survey method**: Terrestrial LiDAR | **Survey date**: 10/3/2019



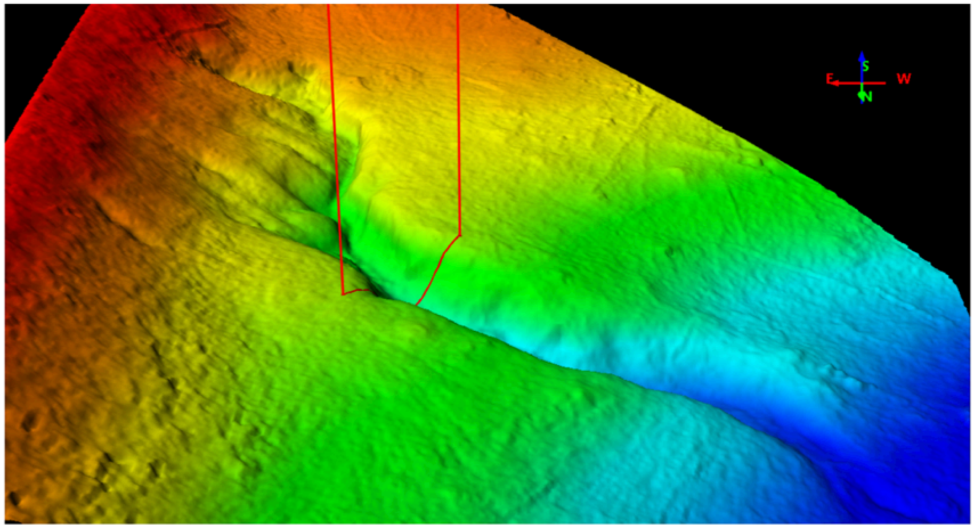
Site name: Young St, Colchester (10) | **Survey method**: Terrestrial LiDAR | **Survey date**: 10/4/2019



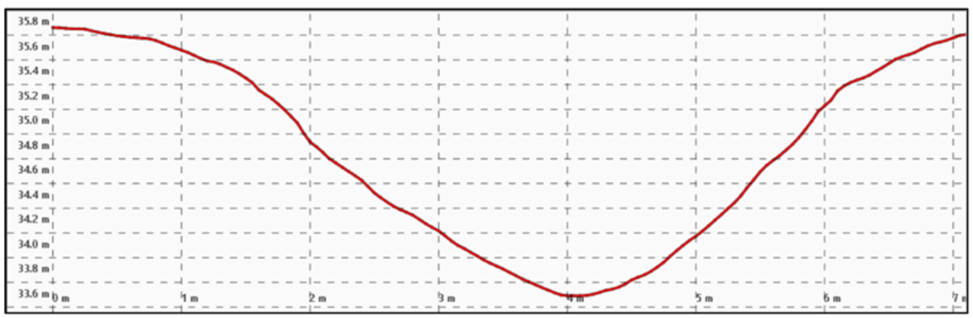
Site name: I89 Waterbury (27) | **Survey method**: Terrestrial LiDAR | **Survey date**: 10/11/2019



Site name: I89 Colchester (3) | **Survey method**: Terrestrial LiDAR | **Survey date**: 10/21/2019



Elevation (0.2 m intervals)



Lateral Distance (meters)

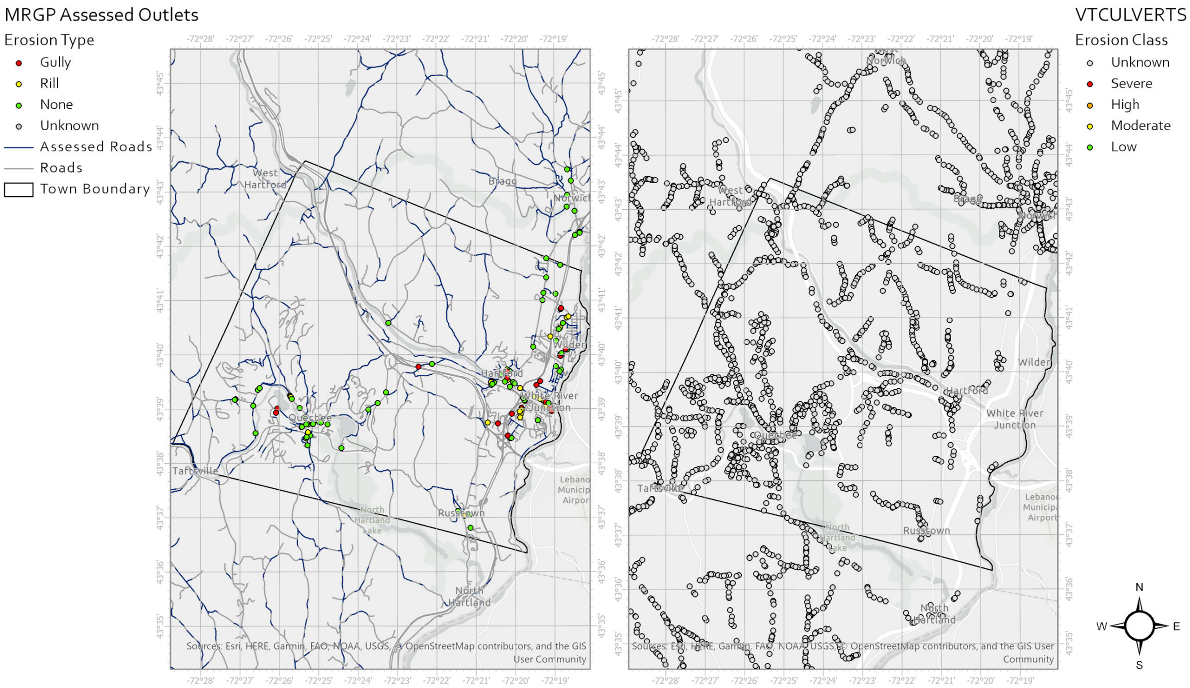
Table A2: Summary of sample bulk densities by depth for all soil samples analyzed from the field sites. Sample Depth is in centimeters below the estimated original ground surface.

Soil Dry Date	Sample Collection Date	Site, Town, (Site ID #)	Sample Depth (cm)	Bulk Density (g/cm^3)
11/11/2019	11/10/2019	Elm Street, Winooski (11)	0-30	1.12
11/11/2019	11/10/2019	Elm Street, Winooski (11)	30-60	1.63
11/11/2019	11/10/2019	Elm Street, Winooski (11)	60-90	1.57
11/11/2019	11/10/2019	Elm Street, Winooski (11)	90-120	1.44
11/11/2019	11/10/2019	Elm Street, Winooski (11)	120-150	1.31
11/11/2019	11/10/2019	Elm Street, Winooski (11)	150-180	1.48
11/11/2019	11/10/2019	Elm Street, Winooski (11)	180-210	1.43
11/11/2019	11/10/2019	Elm Street, Winooski (11)	210-240	1.48
11/11/2019	11/2/2019	Maple Run Lane, Stowe (31)	0-30	0.88
11/11/2019	11/2/2019	Maple Run Lane, Stowe (31)	30-60	1.02
11/11/2019	11/4/2019	Milo White Rd, Jericho (16)	0-30	1.12
11/11/2019	11/4/2019	Milo White Rd, Jericho (16)	30-60	1.19
11/14/2019	10/10/2019	Vale Dr, Essex (15)	0-30	1.33
11/14/2019	10/10/2019	Vale Dr, Essex (15)	30-60	1.45
11/14/2019	10/10/2019	Vale Dr, Essex (15)	60-90	1.29
11/14/2019	10/10/2019	Vale Dr, Essex (15)	90-120	1.34
11/14/2019	10/10/2019	Vale Dr, Essex (15)	120-150	1.35
11/14/2019	10/10/2019	Vale Dr, Essex (15)	150-180	1.40
11/14/2019	10/10/2019	Young St, Colchester (10)	0-30	1.12
11/14/2019	10/10/2019	Young St, Colchester (10)	30-60	1.57
11/14/2019	10/10/2019	Young St, Colchester (10)	60-90	1.43
11/14/2019	10/10/2019	Young St, Colchester (10)	90-120	1.61
11/14/2019	10/10/2019	Young St, Colchester (10)	120-150	1.56
11/14/2019	11/8/2019	I89 Middlesex (28)	0-30	1.19
12/3/2019	11/2/2019	Maple Run Lane, Stowe (30)	0-30	1.17

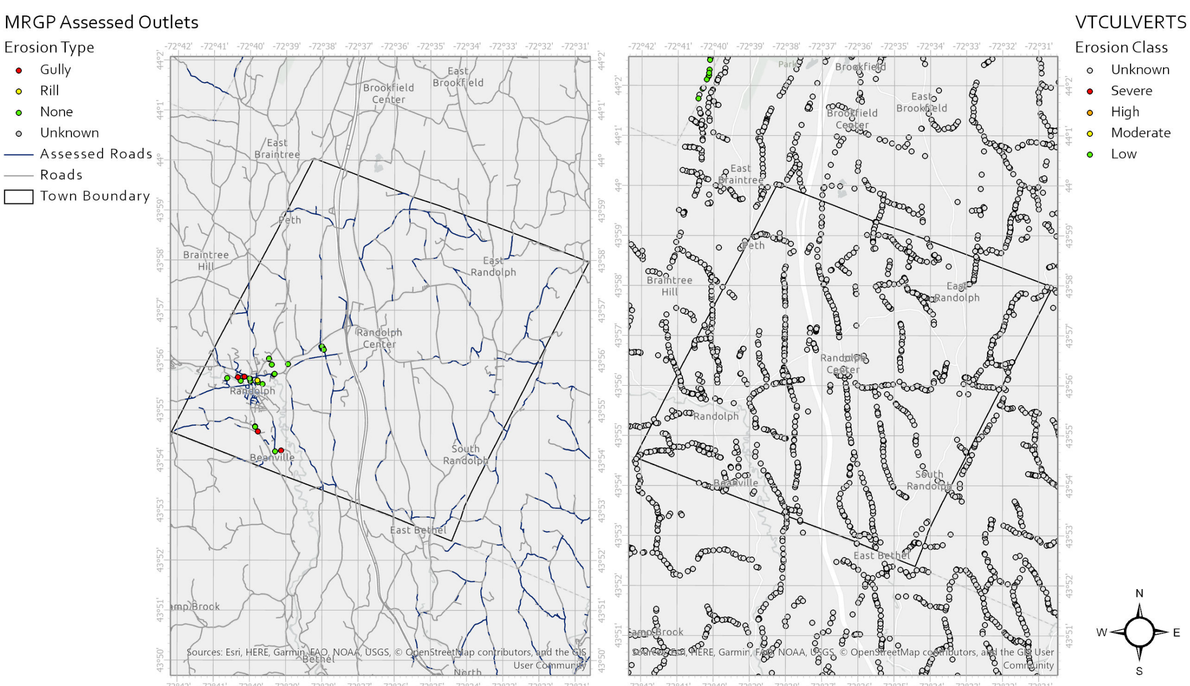
12/3/2019	11/2/2019	Maple Run Lane, Stowe (30)	30-60	1.23
12/3/2019	10/21/2019	I89, Colchester (3)	0-30	0.76
12/3/2019	10/21/2019	I89, Colchester (3)	30-60	0.95
12/3/2019	10/21/2019	I89, Colchester (3)	60-90	0.75
12/3/2019	10/21/2019	I89, Colchester (3)	90-120	0.87
12/3/2019	10/21/2019	I89, Colchester (3)	120-150	1.54
12/3/2019	10/21/2019	I89, Colchester (3)	150-180	1.48
12/3/2019	10/21/2019	I89, Colchester (3)	180-210	1.65
1/13/2020	11/21/2019	I89, Colchester (2)	0-30	1.04
1/13/2020	11/21/2019	I89, Colchester (2)	30-60	1.10
1/13/2020	11/21/2019	I89, Colchester (2)	60-90	1.37
1/13/2020	11/21/2019	I89, Colchester (2)	90-120	1.38
1/13/2020	11/21/2019	I89, Waterbury (27)	0-30	1.36
1/13/2020	11/21/2019	I89, Waterbury (27)	30-60	0.89
1/13/2020	11/21/2019	I89, Waterbury (27)	60-90	1.29
1/13/2020	11/21/2019	I89, Waterbury (27)	90-120	1.19

Figure A2: (3 panels) Coverage of MRGP and VT Culverts datasets in analyzed towns (not including Johnson which was shown in the main text).

Hartford, VT:



Randolph, VT:



Colchester, VT (top) and South Burlington, VT (bottom):

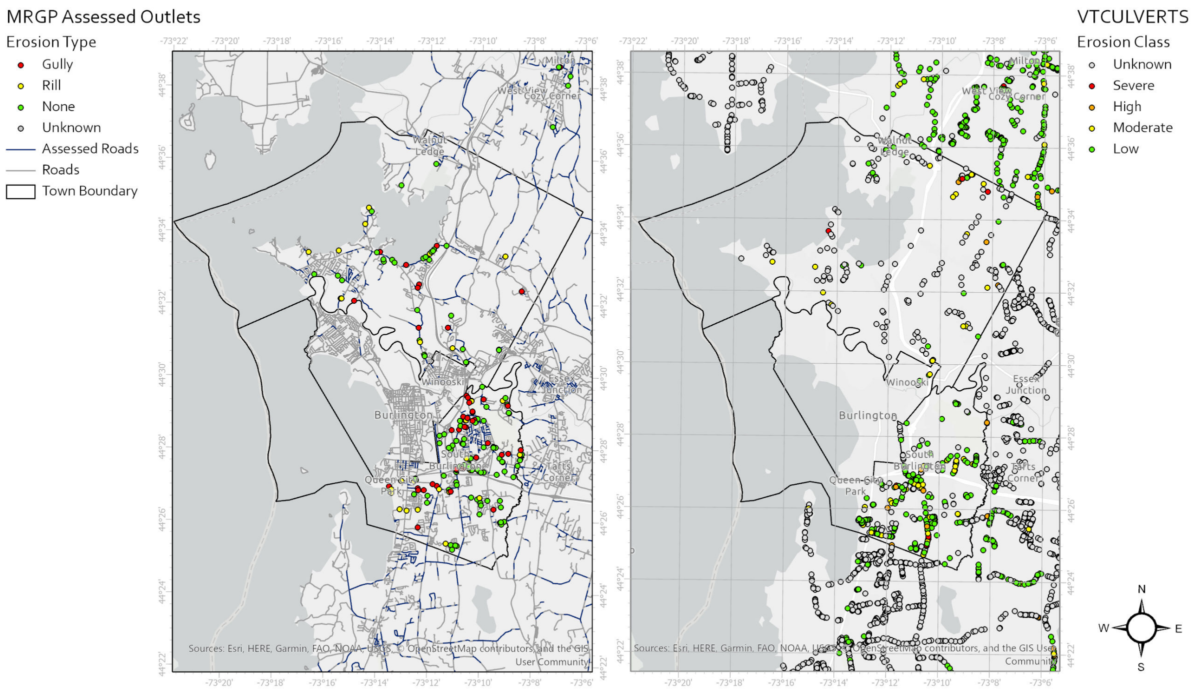


Table A3: ICP results for phosphorus concentrations in collected soil samples from all field sites. Duplicates are from quality control methods. Samples with more than 30 cm range are from final ICP run and were consolidated before analysis. This was due to necessity to get data for all sites before the lab was shut down for the Covid-19 pandemic.

Site Name, Town	Site Number	Depth Range	Phosphorus Concentration (mg/kg soil)
Elm st, Winooski	11	0-30	544.0676535
Elm st, Winooski	11	0-30	537.7275482
Elm st, Winooski	11	30-60	555.6595473
Elm st, Winooski	11	30-60	551.5676833
Elm st, Winooski	11	60-90	627.7741949
Elm st, Winooski	11	60-90	642.8721359
Elm st, Winooski	11	90-120	627.3779331

Elm st, Winooski	11	90-120	613.6393211
Elm st, Winooski	11	120-150	584.9937105
Elm st, Winooski	11	120-150	583.6655835
Elm st, Winooski	11	150-180	678.5888591
Elm st, Winooski	11	150-180	706.111838
Elm st, Winooski	11	180-210	678.1411491
Elm st, Winooski	11	180-210	695.9611585
Elm st, Winooski	11	210-240	726.4803231
I89, Colchester	3	0-30	682.7890827
I89, Colchester	3	0-30	656.581962
I89, Colchester	3	30-60	603.3586434
I89, Colchester	3	60-90	662.8026853
I89, Colchester	3	90-120	620.0979417
I89, Colchester	3	120-150	657.0648148
I89, Colchester	3	150-180	701.0600291
I89, Colchester	3	180-210	635.2261946
I89, Colchester	3	180-210	645.6408259
Vale dr, Essex	15	0-30	620.0205417
Vale dr, Essex	15	0-30	571.1341716
Vale dr, Essex	15	30-60	565.9052063
Vale dr, Essex	15	60-90	537.0216603
Vale dr, Essex	15	90-120	635.4085726
Vale dr, Essex	15	120-150	589.1409106
Vale dr, Essex	15	150-180	612.616908
I89, Colchester	2	0-30	718.886417
I89, Colchester	2	30-60	924.4039817
I89, Colchester	2	60-90	820.07021
I89, Colchester	2	60-90	821.9562673
I89, Colchester	2	90-120	778.1248738
I89, Waterbury	27	0-30	476.9368023
I89, Waterbury	27	30-120	577.3532548
Milo White rd, Jericho	16	0-60	682.6366789
Maple Run ln, Stowe	30	0-60	613.8892299

Maple Run ln, Stowe	31	0-30	529.8371713
Maple Run ln, Stowe	31	30-60	626.9048821
Maple Run ln, Stowe	31	30-60	473.1288722
Young st, Colchester	10	0-30	577.1756387
Young st, Colchester	10	30-60	448.4900269
Young st, Colchester	10	60-150	467.2481157
Young st, Colchester	10	60-150	481.5536803
Quality Control	Oldham 1	n/a	451.1084514
Quality Control	Oldham 2	n/a	471.2796373
Quality Control	Oldham 3	n/a	474.1466986
Quality Control	Oldham 4	n/a	422.1812338